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Original Research

Optimal Sizing and Analysis of Budget-Constrained Solar PV-Grid Systems

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Abstract

The global transition to sustainable energy has increased the adoption of solar photovoltaic (PV) systems, but high initial costs remain a barrier in developing nations like Nigeria. This study evaluates the optimal sizing and feasibility of a budget-constrained solar PV system to supplement grid power for a suburban grocery store. Using HOMER software, six locations in Nigeria were simulated within a \$1,600 budget. The optimal design included a 1.5 kW solar PV system, two 12V 200AH batteries, and a 2.5 kW inverter, costing \$1,554. Ughelli achieved the lowest cost of energy (CoE) at \$0.0712/kWh and a net present cost (NPC) of \$4,039, while Talata Mafara recorded the highest CoE at \$0.0731/kWh and an NPC of \$4,414, underscoring the need for site-specific designs. Northern locations (Talata Mafara, Dikwa, Karu) showed higher solar contributions (32.3%, 32.1%, 30.4%), while southern sites (Ughelli, Ilaro, Amuzu) had lower contributions (26.5%, 27.4%, 28.6%). Despite optimization, unmet energy demand persisted, particularly in southern regions. Excess electricity generation highlights opportunities for improved energy management through enhanced battery storage and demand-side strategies.

KEYWORDS: Energy Solutions, Initial Capital, Optimal Sizing, Solar Photovoltaic, Undersized Systems,

1 INTRODUCTION

The global energy landscape is rapidly transitioning toward renewable energy sources (RES) due to increasing energy demand, diminishing fossil fuel reserves, and growing environmental concerns. Among the various RES technologies, solar photovoltaic (PV) systems have emerged as a leading choice for electricity generation. In 2023, global renewable capacity expanded by 536 GW, with solar PV contributing a significant 407 GW, representing 34% of the total increase [1]. This growth highlights solar PV's increasing dominance in the renewable energy sector across residential, commercial, agricultural, and utility-scale applications [2], [3], [4], [5].

The surge in solar PV adoption is driven by technological advancements and a reduction in component costs. In 2023, global investments in renewable energy rose by 8.1%, reaching USD 622.5 billion [1]. However, the high cost of capital in developing regions, particularly in sub-Saharan Africa, has hindered large-scale renewable energy deployments [6], [7], [8]. Nigeria, despite having abundant solar resources, faces significant challenges in adopting solar PV systems due to high poverty levels, inadequate financial resources, and unreliable electricity supply [9]. Policies such as Nigeria's Renewable Energy Master Plan aim to accelerate the transition to RES, but implementation has yet to yield the anticipated results [10], [11]. In response, many Nigerians are adopting small-scale solar home systems through Pay-As-You-Go (PAYGO) financing models, offering an alternative to conventional backup generators [12], [13].

While several studies have analysed the feasibility of solar PV systems in Nigeria, most focus on system design without considering the financial constraints of potential users. For instance, [14] analysed the feasibility of a standalone solar PV power plant for a housing estate in Abuja. Using PVsyst software, the study found that a 360 kWp system could meet the estate's energy demand, with a positive net present value and high solar fraction. This indicates the economic viability of solar PV in Abuja, despite its high initial cost. [15] and [16] demonstrated the potential of solar PV systems as a sustainable and economically viable alternative to power generators in Nigeria. While the former focused on addressing the country's electricity shortfalls, the later specifically examined the case of Lagos. Both studies demonstrate significant cost savings and environmental benefits associated with solar PV adoption. In commercial applications, [17] proposed a swarm of grid-connected home solar PVs for Nigeria's commercial sector, tackling electricity outages, fostering economic growth, and highlighting the potential for industry expansion through improved power access. [18] assessed the feasibility of a 232-kW solar PV system for supermarkets in Port Harcourt, Nigeria, to reduce reliance on costly diesel generators. With a \$0.14/kWh levelized cost, 4-year payback, and a positive NPV of \$165,322, the system offers financial viability and annual carbon savings of 582 tCO₂. [19] highlighted the challenges associated with the adoption of solar PV systems in Nigeria, primarily due to high initial capital costs compared to the national grid and diesel generators. Despite these financial barriers, the study concluded that PV systems remain a sustainable option for optimising energy in the country, offering long-term environmental and economic benefits. This assertion is supported by other studies, including those on specialised facilities such as health centres [20], street lighting systems that achieved over 80% energy savings compared to grid-powered metal halide systems [21], and livestock farms, where the potential for sustainability and cost reduction was demonstrated [22].

Moreover, existing studies in other regions have highlighted the importance of considering budget limitations in solar PV adoption. Studies in Morocco [23], Algeria [24], and Turkey [25] have demonstrated the economic benefits of PV-grid systems, emphasizing the role of financial planning in ensuring project viability. [25] evaluated the economic viability of 5 kW rooftop PVs in Turkey under the current feed-in-tariff (FiT) scheme, revealing regional disparities, with feasibility limited to the southern province based on predefined financial metrics. [26] presents a techno-economic assessment of a grid-connected PV system for a domestic building in Nottingham, UK, revealing sufficient energy production and achieving a positive net present value under the FiT scheme. Furthermore, a techno-economic assessment of residential grid-connected PV-battery systems in Sweden, conducted by [27], revealed the significance of demand charges in determining their profitability. The study by [28], examines the economic feasibility of residential solar PV systems in Romania under new legislation. It evaluates six system sizes in 18 cities, considering factors like subsidies, energy production, and financial metrics. Results indicate that smaller systems with subsidies are more economically viable. In [29], the economic feasibility of residential solar PV systems in nine global cities was investigated. Factors like annual production, load matching, and

CoE were evaluated. While CoEs varied, NPCs were generally negative, indicating limited economic viability. Besides, the primary concerns of the consumers are the reliability of the supply and the cost of PV-generated electricity. Similarly, [30] noted that the viability of solar PV systems is also determined by factors such as investment costs, electricity tariffs, government incentives, and solar radiation. Other relevant studies are reported for China [31], [32], Dominican Republic [33], Greece [34], and Indonesia [35]. While these studies demonstrated solar PV's technical and economic potential, they failed to explicitly consider how limited budgets impact system sizing and implementation as apparent in Table 1. This gap in the literature necessitates a more comprehensive approach to optimizing solar PV systems within the financial constraints of consumers.

Table 1: Comparison of selected literature site geographical characteristic

Ref.	Objective	Key Findings	Limitations	Relevance	Region/ Country
[23]	Compare polycrystalline and monocrystalline PV systems	Poly-Si modules showed higher final yield compared to Mono-Si. Performance in Meknes exceeded other regions.	Focused to specific PV technologies.	Highlights PV performance comparisons.	Meknes, Morocco
[24]	Design methodology for rooftop PV systems	Identified optimal rooftop zones, PV technologies, and strategies for cost minimization and grid parity.	Limited to rooftop systems.	Demonstrates design methodology.	Ouargla, Algeria
[25]	Assess economic feasibility of 5 kW rooftop PV systems	Higher FiT rates and lower initial costs improve feasibility. Canakkale met viability criteria.	Regional disparities in feasibility.	Emphasizes economic viability.	Turkey (Several cities)
[27]	Evaluate PV-battery systems for residential use	Annual net savings compared to ONLY-GRID; load profiles and demand tariffs influenced performance.	Excluded disposal and recycling costs.	Highlights impact of tariffs and load profiles.	Sweden
[28]	Analyze economic feasibility of residential PV systems	Smaller systems with subsidies showed better feasibility. Sensitivity analysis highlighted energy prices.	Limited to residential applications.	Demonstrates feasibility under subsidies.	Romania (18 cities)

[14]	Feasibility study for standalone solar PV in housing estates	360 kWp system met energy demand with positive NPV. LCOE below Nigeria's subsidized tariff.	High initial cost barrier.	Addresses standalone system feasibility.	Abuja, Nigeria
[18]	Assess solar PV for supermarkets to reduce diesel reliance	232 kW system offered financial viability and carbon savings. LCOE: \$0.14/kWh, 4-year payback.	Limited to commercial applications.	Highlights cost savings and environmental benefits.	Port Harcourt, Nigeria
[21]	Evaluate solar PV for street lighting systems	Identified high initial costs as a barrier but confirmed long-term sustainability of PV systems.	Broad focus without detailed financial analysis.	Supports long-term viability of PV systems.	Nigeria
This Study	Optimal sizing and analysis of budget-constrained PV-grid systems	Developed a framework for optimizing solar PV systems under financial constraints. Identified cost-effective solutions based on Initial capital.	Focused on budget limitations; limited to Nigeria.	Fills gap in budget-constrained optimization.	Nigeria (Multiple Sites)

Apparently, existing studies on solar PV systems have largely focused on grid-connected applications, techno-economic assessments, and performance evaluations in various regions [36], [37], [38], [39]. However, these studies ignored the financial capacity of end-users and fail to provide a framework for optimizing system sizing based on available budgets. This gap is particularly critical in Nigeria, where the majority of potential solar PV adopters operate under severe financial constraints.

This study addresses this gap by developing a design and simulation framework for optimizing solar PV systems under limited financial constraints. Specifically, the research aims to:

1. Develop a design and simulation framework for optimizing solar PV systems that aligns with the budgetary limitations of prospective owners.
2. Assess the technical performance of these systems using data from representative sites across Nigeria.
3. Conduct an economic analysis to identify the most cost-effective solutions based on key financial parameters.

By focusing on budget-constrained optimization, this study provides valuable insights for individuals and organizations seeking to invest in solar PV systems while balancing financial limitations, unreliable power supply, and sustainability. The findings are particularly relevant for Nigeria and other developing countries, where the transition to renewable energy is critical for achieving energy security and sustainable development goals.

2 MATERIALS AND METHOD

This study investigates the feasibility of utilising a budget-constrained solar PV system to supplement grid power for a typical suburban grocery shop in Nigeria's diverse climatic regions.

System components and their parameters were defined, and simulations were conducted using HOMER software to evaluate performance. The optimal system configuration with the lowest initial cost which is within the pre-defined budget was selected. Control parameters such as the number of solar panels, inverter size, and battery capacity were adjusted to meet the shop's energy demand while staying within financial limits. Critical variables including daily load demand and site-specific solar energy availability were also considered in assessing system performance. A detailed discussion of these parameters and their influence on system optimization is provided in ensuing sections.

2.1 Study sites and data description

To ensure a comprehensive assessment, the sites for this study were selected from each of the six geo-political zones of the country, with one site per zone (see Fig. 1). These locations which encompass a variety of climatic conditions, includes Ughelli (South-South), Ilaro (South-West), Amuzu (South-East), Talata Mafara (North-West), Dikwa (North-East), and Karu (North-Central). This careful selection provides a broad representation across the country, facilitating an effective assessment from the study. A summary of the geographical characteristics of these locations is provided in Table 2.

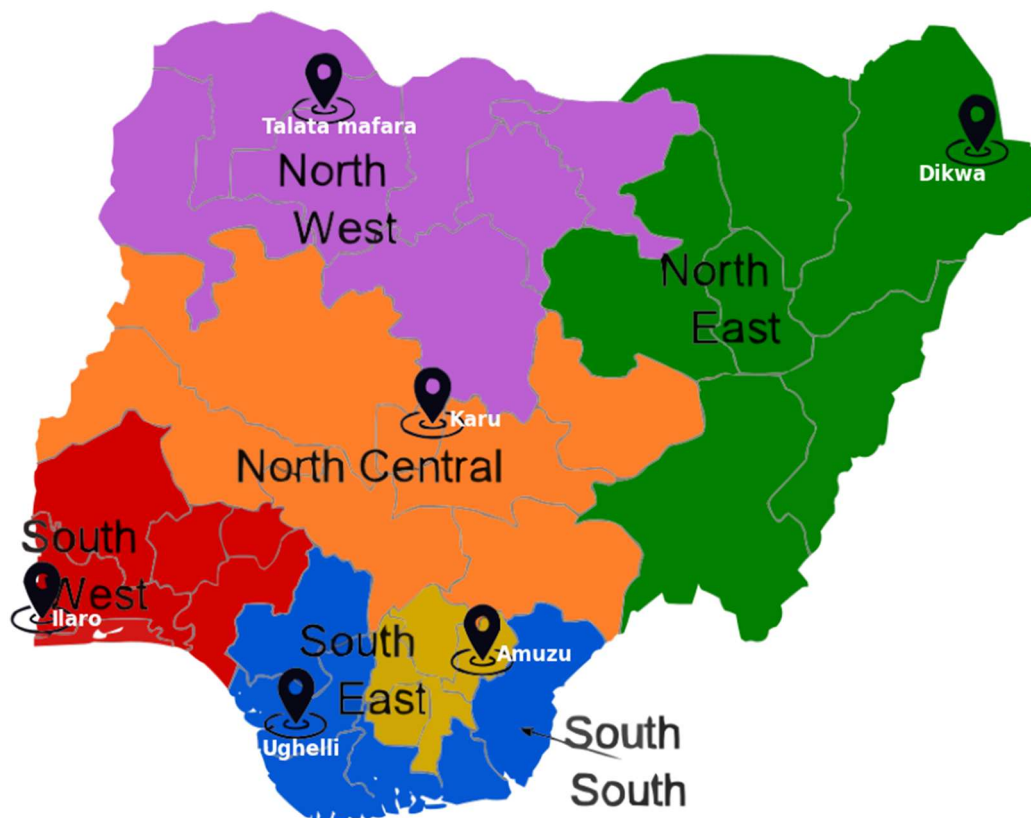


Fig. 1: Map of Nigerian showing the selected location from the different geopolitical zones

Table 2: Selected site geographical characteristic

Location	Zone	Latitude (°N)	Longitude (°E)
Ughelli	South-South	5.53	5.95
Ilaro	South-West	6.55	3.3
Amuzu	South-East	6	7.25
Talata Mafara	North-West	11.5	7
Dikwa	North-East	11.93	13.48
Karu	North-Central	9.05	7.42

2.2 Loads profile

A typical street-side grocery store in most Nigerian sub-urban towns has several electrical loads

with different energy consumption pattern, such as lighting essential for any commercial space, fans for space colling, and refrigeration system for preserving perishables. This information is used to estimate a typical 24 h load profile shown in Fig. 2 using typical rating of such systems outlined in Table 3.

Table 3: Electrical equipment and energy consumption within the store

Equipment	Load (kW)	Hours	Energy Consumption (kWh/day)
Lighting (indoor)	0.5	8	4
Lighting (outdoor)	0.8	12	9.6
Fans	1.4	5	7
POS systems	0.1	6	0.6
Computers	0.2	6	1.2
Refrigeration	0.45	14	6.3
Total			31.3

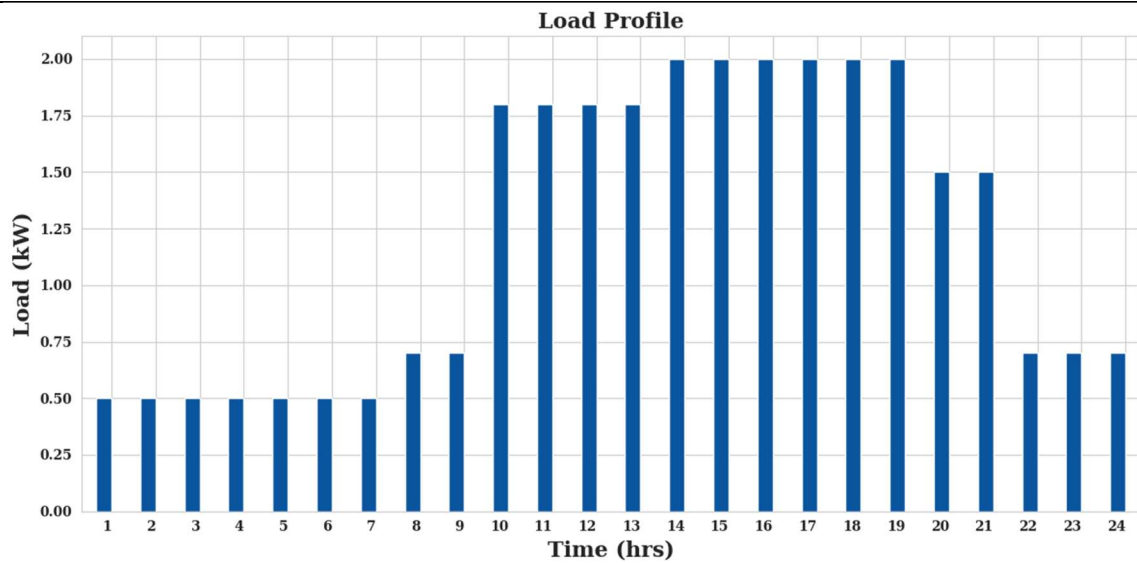


Fig. 2: Load profile of a typical grocery store in Nigeria

2.3 Solar Energy Potential

Nigeria, located close to the equator, is rich with high solar irradiance. In this section, the selected sites are considered in order to determine the available solar energy resources. The solar radiation distribution in Nigeria is shown in Fig. 3, while Fig. 4 and Fig. 5, respectively, shows the actual monthly solar radiation and clearness index for all the selected locations. The monthly mean solar intensity on horizontal surfaces across the selected sites which was obtained from the NASA website indicates variation from a minimum of 3.51 kWh/m² in Ughelli at the peak of the rainy season in July and a maximum of 6.95 kWh/m² in Dikwa just before the rains fully sets in in April.

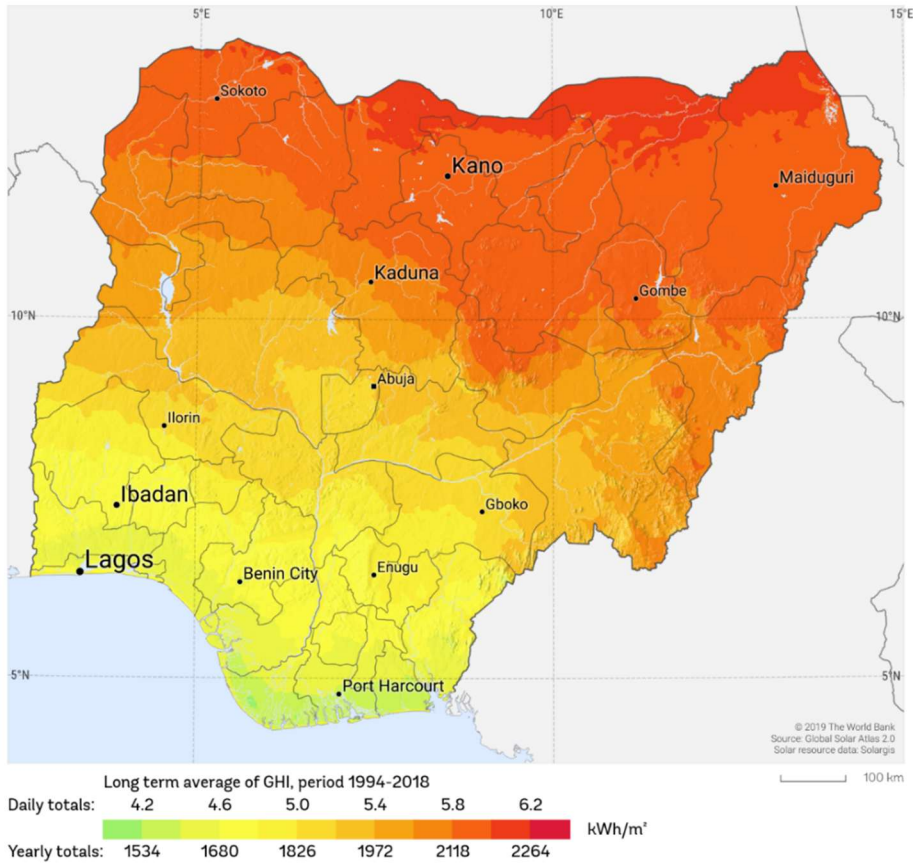


Fig. 3: Global horizontal solar irradiance distribution across Nigeria [40]

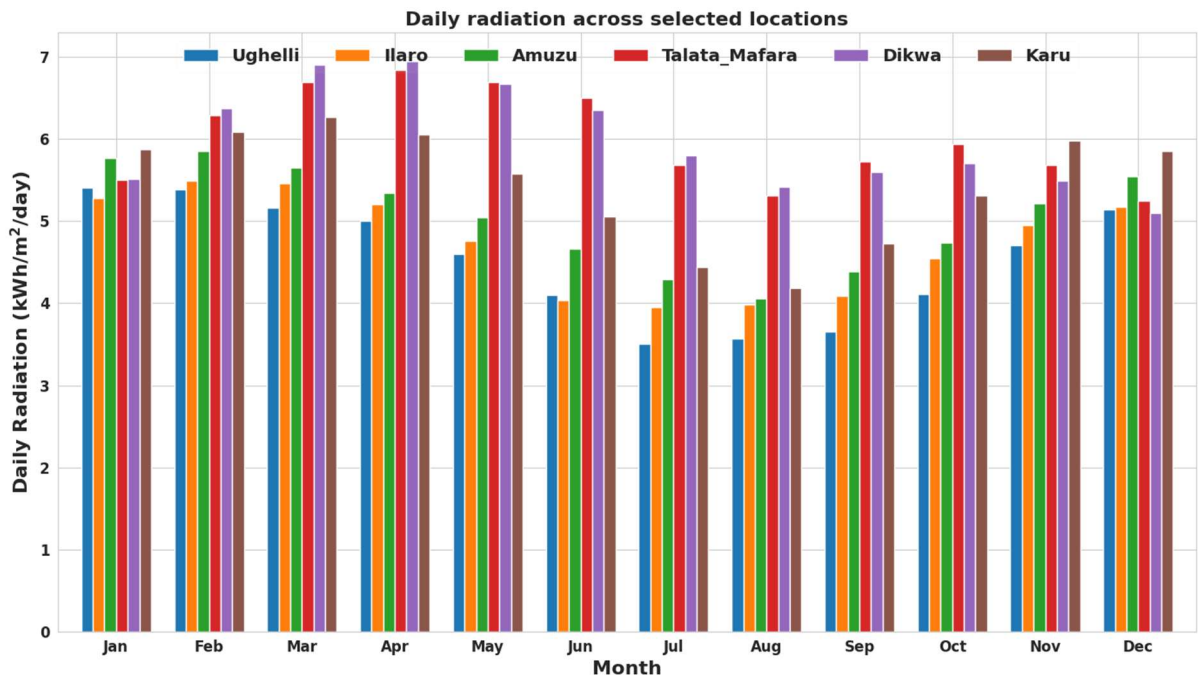


Fig. 4: Average daily solar radiation for the selected location in the study

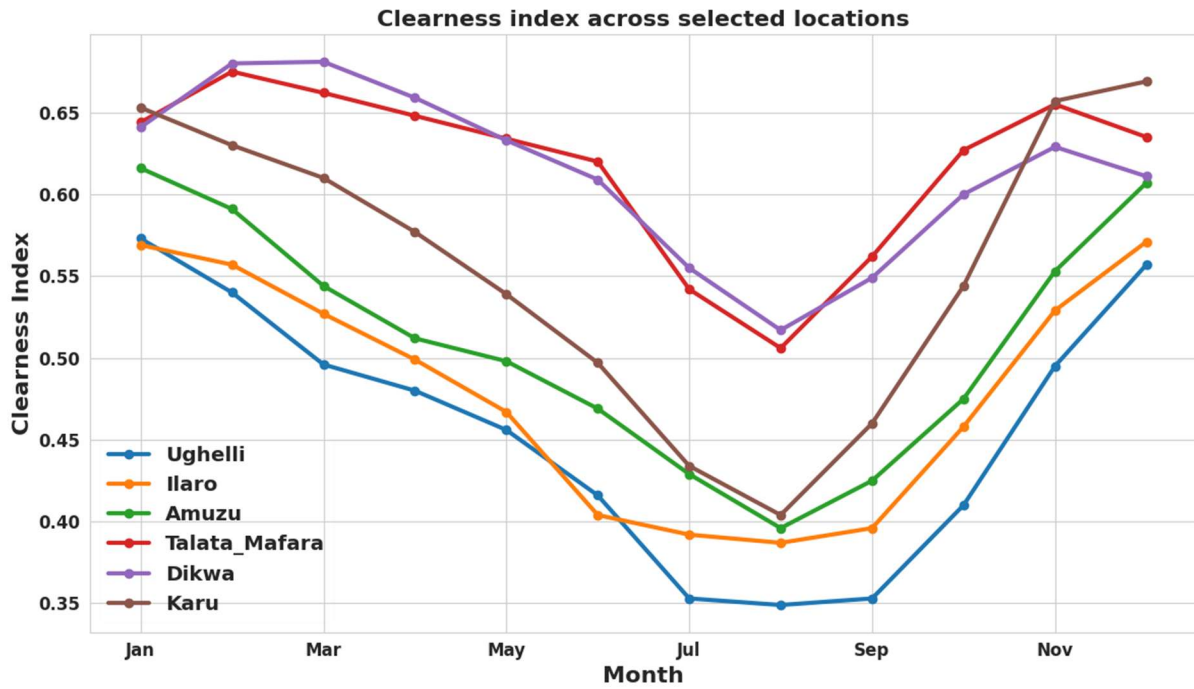


Fig. 5: Clearness index for the selected location in the study

2.4 System components modelling

The unreliable nature of electricity from the national grid in Nigeria has driven an increase in the use of RES, particularly solar photovoltaic (PV) systems. However, this alternative remains inaccessible to many due to the high upfront costs, which exceed the budget of the average intending owner. Consequently, identifying an optimal system size with an economically efficient configuration that aligns with the financial capacity of potential users becomes essential. The proposed design for the grid-connected system is shown in Fig. 6.

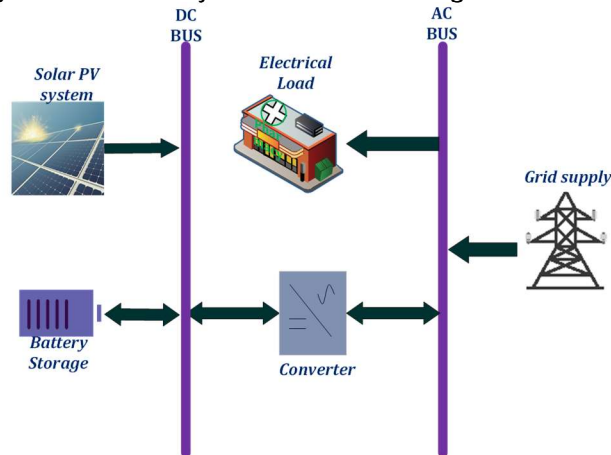


Fig. 6: Schematic of the system under study

2.4.1 System design and simulation with HOMER

We used the Hybrid Optimization Model for Electric Renewables (HOMER) for the modelling and simulation of the optimal sizing design of the study system. HOMER is a versatile tool capable of determining feasible solutions for renewable energy systems based on specified technical, economic, and available resource input parameters. It also allows for the performance evaluation of each system component throughout the project lifecycle. Fig. 7 illustrates the framework adopted in this research to identify the optimal solution that meets the energy demand of the store while considering the financial capacity of the store owner. The input parameters for HOMER simulation include the load profile, solar resource data, system control settings, constraint parameters, and

the technical and cost details of the system components. A crucial step in the HOMER simulation process was the tuning of the maximum capacity shortage constraint, which was iteratively adjusted to find the optimal system configuration within the consumer's budget, and this process was thereafter repeated for each of the selected locations

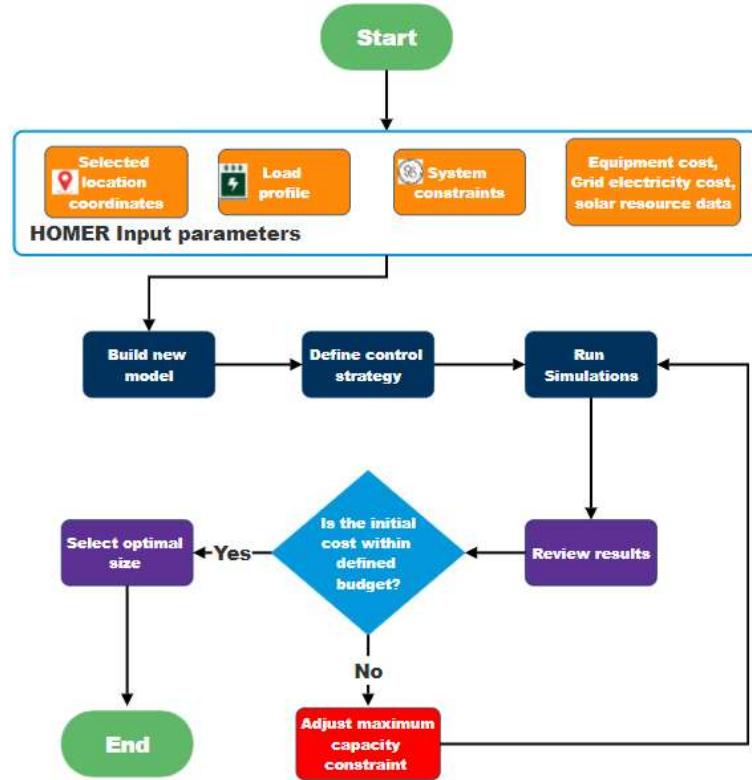


Fig. 7: Study implementation framework in HOMER

2.4.2 Solar PV model

The electrical power obtainable from a photovoltaic (PV) module depends on several factors, including the location's solar resources, the surface area of the solar panel, and others, as described by equation (1) [41]. The expression is used to calculate the energy output of a rated PV module under Standard Test Conditions (STC), which are defined as 1 kW/m² irradiance and a cell temperature of 25°C.

$$P_{PV} = P_{PV} \times f_{PV} \left(\frac{G_T}{G_{T-STC}} \right) (1 - \alpha (T_c - T_{c_STC})) \quad (1)$$

In this study, HOMER simulation incorporated a Jinko 250RX PV panel (250 W rated capacity, \$56.39 capital cost) with performance parameters defined as follows: P_{PV} represents the PV's rated capacity while f_{PV} accounts for its derating factor. Solar radiation values are captured by G_T (current incident radiation) and G_{T-STC} (incident radiation under Standard Test Conditions). Temperature effects are quantified through α (power temperature coefficient of 0.5), T_c (current cell temperature), and T_{c_STC} (cell temperature at Standard Test Conditions, 25°C) [41].

2.4.3 Battery storage

The performance of most PV systems is better complimented with the use of battery storage system. The battery system stores energy from the solar system and enables the continuous supply of energy to the load in periods of low or no solar radiation and during grid outage [42]. The amount of stored energy is computed using equation (2) [41].

$$E_{bat} = \frac{P_D \times D_{at}}{\eta_{bat} \times DoD \times V_{DC_sys}} \quad (2)$$

Where P_D is the electrical load to be supplied, D_{at} are the days of battery autonomy, η_{bat} is the

round-trip efficiency of the battery, DoD is the depth of discharge, and V_{DC_sys} is the nominal voltage of the system. Equations (5) and (6) address the issue of over-charging or over-discharging of the battery system:

$$B_{s:min} \leq B_s \leq B_{s:max} \quad (3)$$

$$B_{s:min} = (1 - DoD_{max}) \times B_s \quad (4)$$

$$B_{s:min} = SoC_{min} \times B_s \quad (5)$$

Where:

$B_{s:min}$ is the minimum battery size,

B_s is the battery size,

$B_{s:max}$ is the maximum battery size,

DoD_{max} is the maximum depth of discharge, and

SoC_{min} is the minimum state of charge at a given time.

As part of measure to prolong the life time of the storage systems, the state of charge of the battery is maintained using the following:

$$SoC_{min} \leq SoC(i) \leq SoC_{max} \quad (6)$$

In this study, a Trojan SAGM 12V 205AH dry cell battery is used in the design simulation setup costing \$ 506.53/unit.

2.4.4 Converter

The energy stored in the battery system is transformed from DC to AC supply required for use by the electrical load using a converter system. This system is also designed to convert grid supply for charging of the battery as a bi-directional configuration. An efficiency of 95% is assumed for the converter used in this study with a lifespan of up to 15 years. The converter is sized to ensure the peak load of the system can be served. This is expressed as [41]:

$$P_{conv} = \frac{P_{max}}{\eta_{inv}} \quad (7)$$

$$\eta_{inv} = \frac{P_{output}}{P_{input}} \quad (8)$$

2.4.5 Grid supply system

The system under investigation is connected to the Nigerian national grid, which is characterised by its intermittent and unreliable supply. This study assumes an average daily supply of approximately 12 hours with varying outage times. The average electricity cost for such consumers in this context is \$0.033/kWh. Fig. 8 represents the grid's unreliable supply and outage patterns.

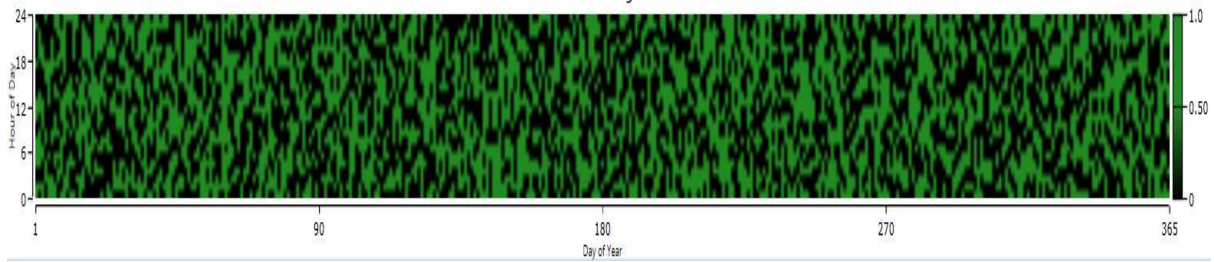


Fig. 8. Grid supply indicating power outages

2.5 Econometric indices

Traditionally, the economic performance indices used in most study to select the optimal combination of system includes the cost of energy (CoE), and the net present cost (NPC), which are elaborated in the following sections. In this study however, the primary economic criterion of significant implication is the total initial capital cost of system. This ensures an optimal system that is within the budget of a potential owner of the system.

2.5.1 Net Present Cost

The net present cost (NPC), also known as the life-cycle cost, measures the present value of all costs associated with a system component throughout its project lifetime. These costs include installation, operation, and maintenance. The NPC subtracts the present value of all revenues generated over the project lifetime, providing a crucial indicator of the investment's profitability. The NPC is calculated using the (9) [2]:

$$NPC = \frac{C_{TAC}}{CRF(i, N)} \quad (9)$$

Where C_{TAC} , CRF , i , and N represents the total annualised cost (\$/year), capital recovery factor, real discount rate, and project lifetime respectively. The CRF , shown in equation **Error! Reference source not found.**, calculates the present value of an annuity and is defined as [2]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (10)$$

2.5.2 Cost of energy

The cost of energy (CoE) is a metric that represents the average cost per kilowatt-hour (kWh) of useful electrical energy produced by a system over its lifetime. This cost metric provides a comprehensive measure by including all costs associated with the system's lifecycle, from initial capital investment to operations and maintenance, and eventual replacement. The CoE is calculated using the following formula [2]:

$$CoE = \frac{C_{TAC}}{E_{SERVED}} \quad (11)$$

where E_{served} is the primary load served per year (kWh/year).

3 RESULTS AND DISCUSSION

3.1 Optimisation results

The optimal sizing of the solar PV system for each selected location was determined using site-specific solar resource data and the corresponding load profiles, as illustrated in Fig. 2. The results presented in this section demonstrate the viability of the solar PV system in supporting a grid-connected load with intermittent supply, contingent on several key factors. This study focuses on

the owners' financial capacity to acquire the PV system components, the solar resource availability at each location, and the overall lifecycle costs of the system configurations.

A year-long, hourly simulation using the HOMER platform, as detailed in Fig. 7, was conducted to assess the performance of the optimal system design. Key performance metrics such as annual electricity production, load served, excess electricity, and unmet demand were analysed to provide a comprehensive evaluation of the system's operational efficiency under varying conditions.

HOMER's simulation results were initially ranked based on the lowest NPC, offering a long-term economic perspective. However, this study further refines the ranking by prioritising systems that meet a predefined budget threshold, with the initial capital cost set at \$1,600, reflecting the owners' limited financial constraints. Simulations results showed that the optimal system configuration—a 1.5-kW PV array, two batteries, and a 2.5-kW inverter—was uniformly identified across all six locations (Table 4) at an initial capital expenditure of \$1,554 which is within the strict \$1,600 budget constraint. While this configuration is undersized for the load demand, it represents a critical trade-off between financial limitations and technical feasibility. Notably, the uniformity in sizing despite varying solar resources (e.g., Talata Mafara's higher irradiance vs. Ughelli's lower potential) underscores the dominance of budget constraints over site-specific optimization in this study.

Table 4: Optimal size result of the system with the least initial capital

Components size			Location	Econometrics		
Solar PV (kW)	Battery (nos)	Converter (kW)		Initial capital (\$)	NPC (\$)	CoE (\$)
1.5	2	2.5	Ughelli	1,554	4,039	0.0712
			Ilaro		4,100	0.0715
			Amuzu		4,173	0.0719
			Talata Mafara		4,414	0.0731
			Dikwa		4,389	0.0729
			Karu		4,278	0.0723

3.2 Economic analysis

Further analysis of NPC and CoE reveals significant variations in long-term economic performance across the locations. Ughelli emerged as the most economically favourable site, with the lowest NPC at \$4,039 and a CoE of \$0.0712, reflecting efficient energy production relative to costs. This suggests Ughelli offers superior long-term financial sustainability, with the same initial cost. In contrast, sites such as Ilaro, Amuzu, Talata Mafara, Dikwa, and Karu exhibit higher NPCs ranging from \$4,100 to \$4,414, with corresponding CoEs between \$0.0715 and \$0.0731. These variations in CoE among the sites, though minimal, are important for understanding the economic viability of cost constrained solar PV systems across the different regions in Nigeria. More specifically, Talata Mafara, which incurs the highest NPC of \$4,414 and CoE of \$0.0731, provides a typical case of the consequences of higher energy production potential on cost. While this site offers more energy generation potential with increased energy production, it resulted in an underutilised capacity and higher long-term costs. This raises important considerations regarding the balance between initial system design cost and long-term operational cost efficiency. The higher NPC and CoE values, as observed in Talata Mafara, highlight a trade-off between maximising energy generation and achieving cost efficiency, emphasising the need for site-specific design strategies. Contrary to [25]'s finding that FiT rates drive viability in Turkey, our Nigerian case shows budget constraints dominate – even with similar solar resource potentials. This suggests developing economies may need fundamentally different incentive structures. The findings confirm that financial constraints significantly alter the traditional metrics of PV system optimization, with long-term costs (NPC) being more sensitive to grid reliability than solar potential in budget-limited scenarios.

3.3 Energy production analysis

Fig. 9, illustrates the monthly average annual electricity production from the undersized solar

PV-grid system across the selected sites. It is observed that the grid system sustained the bulk of the energy requirement of the load compared to the budget-constrained undersized PV system. Table 5 summarises the annual total energy production of the six locations alongside the percentage contributions of both solar PV and grid supply to the overall energy mix. The total energy supplied varies across the six locations, ranges from 7,751 kWh/yr in Ughelli to 8,416 kWh/yr in Talata Mafara. The other locations—Amuzu, Dikwa, Karu, and Ilaro—showed total energy supply records, falling between 7,850 kWh/yr and 8,191 kWh/yr. In terms of solar energy contribution, Talata Mafara has the highest solar energy production at 2,716 kWh/yr, which accounts for 32.3% of its total energy supplied. Dikwa follows closely with 2,688 kWh/yr of solar energy, contributing 32.1% of its total energy. Conversely, Ughelli records the lowest solar energy produced, with 2,052 kWh/yr, contributing 26.5% of its total energy delivered. Similarly, Ilaro and Amuzu show slightly higher contributions from solar energy, at 27.4% and 28.6%, respectively. Karu had a solar contribution of 2,491 kWh/yr, which makes up 30.4% of its total energy produced, marking a substantial contribution to its energy mix. The varying solar energy contributions across the locations are largely influenced by differences in solar irradiance, and regional climatic conditions, with northern regions generally receiving higher levels of solar radiation than southern regions. The grid energy delivered is consistent with an average of 70.45 % across all six locations, with only minor variations in total grid-supplied energy. The apparent higher supply from the grid in locations like Ughelli and Ilaro confirms that the solar energy potential in these regions is less compared to regions like Talata Mafara and Dikwa.



Fig. 9: Monthly average electricity production for the selected location

Table 5: Total annual energy produced for optimally sized system

Location	Electrical Production Summary			Total Consumption (kWh/yr)	Excess Electricity (kWh/yr)	Unmet Load (kWh/yr)	Capacity Shortage (kWh/yr)
	Solar (kWh/%)	Grid (kWh/%)	Total (kWh/yr)				
Ughelli	2,052 / 26.5%	5,700 / 73.5%	7,751	7,238	178	4,143	4,354
Ilaro	2,151 / 27.4%	5,700 / 72.6%	7,850	7,309	191	4,072	4,294
Amuzu	2,286 / 28.6%	5,700 / 71.4%	7,986	7,405	211	3,976	4,210
Talata Mafara	2,716 / 32.3%	5,700 / 67.7%	8,416	7,701	282	3,679	3,954
Dikwa	2,688 / 32.1%	5,691 / 67.9%	8,379	7,682	268	3,699	3,966
Karu	2,491 / 30.4%	5,700 / 69.6%	8,191	7,546	245	3,835	4,088

Other data from Table 5 also reveals notable differences in energy consumption pattern, unmet loads, capacity shortages, and excess electricity. The comparative analysis across the six regions highlights both the strengths and limitations of the optimally sized systems in responding to the specific energy demands and solar resource availability of each site. In terms of total energy consumption, all locations displayed relatively similar values, with Ughelli in the South-South region consuming 7,238 kWh and Talata Mafara in the North-West consuming 7,701 kWh. This consumption pattern aligns with the available solar energy resources and production for the selected sites. However, slight regional differences in consumption could be attributed to variations in solar irradiance which is influenced by climatic conditions and grid availability patterns.

Northern sites like Talata Mafara and Dikwa achieved a 32% solar penetration rate due to higher irradiance, while southern sites such as Ughelli and Ilaro averaged 27%, reflecting Nigeria's solar resource distribution. However, the findings highlight that even in regions with optimal solar potential, budget-driven undersizing remains a limiting factor. Notably, the grid's consistent ~70% contribution across all sites serves as a financial buffer, mitigating PV shortfalls in constrained systems.

Despite the system being oversized, excess electricity production was recorded at all sites. The system produced surplus energy of 178 kWh/yr, 191 kWh/yr, 211 kWh/yr, 282 kWh/yr, 268 kWh/yr, and 245 kWh/yr at Ughelli, Ilaro, Amuzu, Talata Mafara, Dikwa, and Karu, respectively. These values correspond to percentages of excess electricity ranging from 2.3% to 3.35%. The highest excess was recorded in Talata Mafara, a location benefiting from superior solar potential. This excess energy indicates periods when the system's generation exceeded local demand, particularly during high solar radiation days or when grid availability complemented energy production from the PV system. Fig. 10 illustrates a typical scenario in which solar PV generation peaked alongside grid supply, leading to temporary overproduction. While the excess electricity is used to charge the battery storage, it also highlights the potential for optimising energy production by diverting surplus power to other critical loads in future system upgrades. However, the current system's oversized capacity reflects a limitation that can lead to periods of underutilisation, particularly during peak production from the solar PV, further exacerbated by grid availability constraints.

Talata Mafara's excess energy of 282 kWh/yr, representing 3.35% of its production, highlights temporal mismatches between PV generation and demand, as illustrated in Fig. 10, where midday peaks often surpass consumption. This suggests opportunities for load shifting or incorporating ancillary storage in future designs. Conversely, Ughelli's unmet demand of 4,143 kWh/yr, accounting for 38.3% of its total demand, reveals the system's vulnerability to grid outages, challenging the assumption that hybrid PV-grid systems inherently enhance reliability under strict budget constraints.

These results emphasize that budget constraints exacerbate the "energy gap" in regions with poor grid reliability, even when solar resources are abundant.



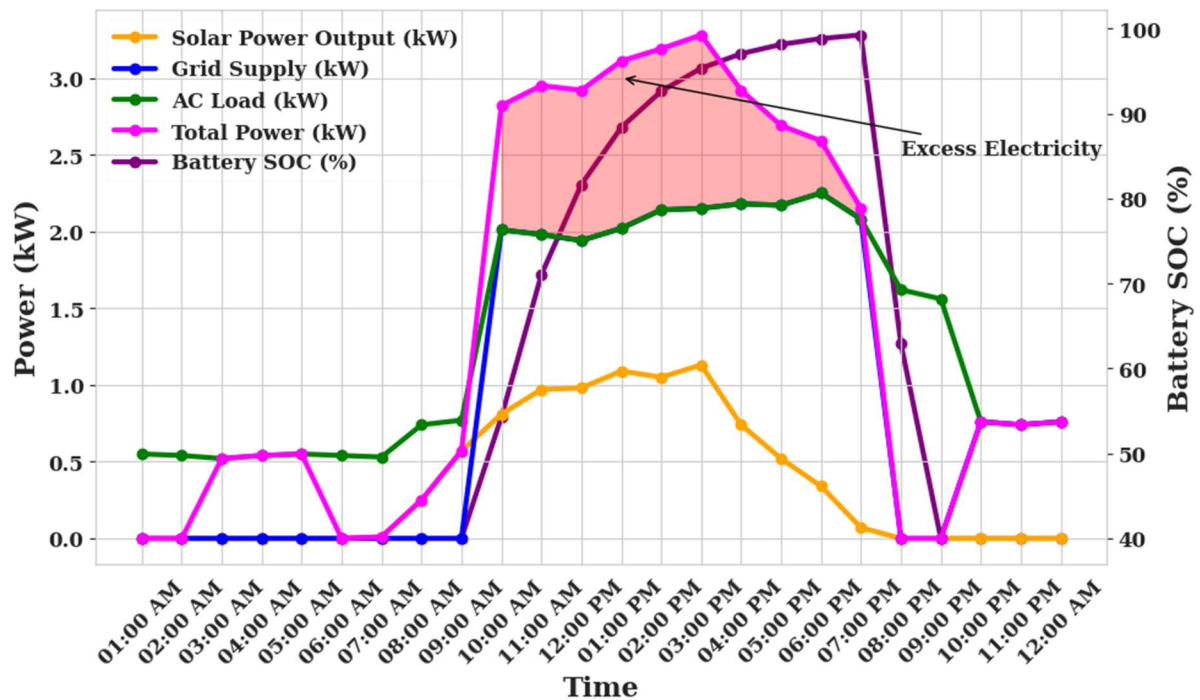


Fig. 10: 24-H energy production and consumption profile showing excess electricity for a Typical day (August 15) in Talata Mafara

On the other hand, the system also experienced significant unmet loads due to periods of low solar generation and grid outages. Unmet loads ranged from 3,679 kWh in Talata Mafara to 4,143 kWh in Ughelli, underscoring the challenges of maintaining a constant energy supply, especially in Nigeria where grid reliability is low. These unmet load figures are significant, revealing that a substantial portion of demand went unsatisfied, particularly during low solar production periods. A similar trend was observed in capacity shortages, with Talata Mafara experiencing the least shortfall at 3,954 kWh and Ughelli the highest at 4,354 kWh. These shortages, representing 34.7% and 38.3% of total demand respectively, highlight the system's inability to meet load requirements for some periods.

These results emphasise the need for site-specific optimisation strategies. While Talata Mafara benefits from higher solar potential, leading to both greater energy production and excess electricity, it also experiences fewer shortages and unmet loads compared to locations like Ughelli. This underscores the importance of balancing system sizing with local grid conditions and solar resource availability. Future improvements, such as integrating storage solutions or enhancing grid reliability, could mitigate both excess electricity production and unmet load scenarios, improving overall system efficiency.

4 PRACTICAL AND POLICY IMPLICATIONS

The adoption of solar photovoltaic (PV) systems in Nigeria offers a promising pathway to improving energy access and reducing reliance on the often, unavailable national grid. However, challenges such as high initial costs—which often lead to system undersizing, energy curtailment, and unmet demand—must be addressed through targeted policy interventions. This study underscores the potential of affordable, off-grid solar PV solutions, particularly for small businesses in rural and suburban areas. The government should prioritize tiered financing models (e.g., pay-as-you-save schemes, microloans) and subsidies for key components like batteries and inverters to lower upfront cost obstacle. Policymakers should further promote adoption through incentives such as tax breaks and tailored financing options, especially in off-grid and underserved regions.

Although the system analysed in this study is small and may not exert a significant direct impact on the national grid, its wider deployment across sectors and regions holds substantial promise. For grid operators, the large-scale adoption of small solar PV systems could collectively reduce grid demand during peak periods, providing relief in regions prone to load shedding or frequent



outages. By supplementing grid power, such systems can help improve overall grid resilience and efficiency. Demand-side management strategies, such as time-of-use tariffs or installation incentives, may further encourage widespread adoption.

For business owners, the study illustrates how solar PV systems can provide long-term cost savings and improved energy reliability, especially in areas with erratic grid supply. These systems not only reduce electricity expenses but also enhance operational continuity, supporting business sustainability. At the community level, small-scale solar solutions can address localized energy scarcity, improve living standards, and support local economic development through job creation and innovation in energy management.

Moreover, the modelling approach presented in this study is adaptable and can be applied to various contexts beyond a suburban grocery stores. By adjusting parameters such as load profiles, solar irradiance, and budget constraints, the framework can be extended to assess solar PV feasibility for residential users, commercial entities, or community energy projects in other regions. This flexibility makes it a valuable tool for policymakers, development agencies, and investors aiming to support decentralized renewable energy solutions across diverse settings.

5 CONCLUSIONS

This study presents an approach to the optimal sizing of budget-constrained solar PV systems for small-scale commercial applications, specifically a typical grocery store, across six different geographical sites in Nigeria. The selected sites—Ughelli (South-South), Ilaro (South-West), Amuzu (South-East), Talata Mafara (North-West), Dikwa (North-East), and Karu (North-Central)—were strategically chosen to provide a comprehensive analysis of regional energy production potentials. The key conclusions of this study are outlined as follows:

1. Through detailed simulations in HOMER, the study identified a uniform financially viable solar PV system configuration consisting of 1.5 kW PV panels, a 2.5 kW inverter, and two 12V 200 AH battery units. The system, with an initial cost of \$1554, fits within the predefined budget limit of \$1600, demonstrating that cost-effective solar energy solutions are achievable even with limited financial resources.
2. The study highlights significant regional differences in solar energy production potential across Nigeria. Northern sites such as Talata Mafara and Dikwa exhibited higher solar energy contributions in both absolute terms and as a percentage of total energy production, while southern locations, including Ughelli and Ilaro, showed reduced potentials.
3. Despite the optimal design, the undersized system led to notable unmet loads and capacity shortages, particularly in the South-South and South-East regions, where solar contributions were lower. This finding emphasises the trade-offs between system affordability and performance, illustrating the limitations of budget-constrained designs in meeting energy demand consistently.
4. The analysis also revealed periods of excess electricity generation, which were used to charge battery storage. This finding suggests an opportunity for improved energy management by expanding storage capacity and adopting demand-side management strategies to better harness and utilise excess electricity, especially in regions with higher solar potential.

Overall, this study contributes a practical framework for the deployment of cost-constrained solar PV systems in Nigeria, while also highlighting the importance of geographical energy dynamics, limitations of undersized systems, and the potential for future improvements through enhanced storage. However, this study is limited by the use of a fixed load profile and a strict budget constraint, which may not capture real-world variability. Future research should consider dynamic load patterns, explore hybrid systems, and assess the impact of different financing models to enhance system performance and scalability.

Data Availability. Data underlying the results presented in this paper are available from the corresponding author upon reasonable request.

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Ethics. The authors declare that the present research work has fulfilled all relevant ethical guidelines required by [COPE](#).



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